STATE OF CALIFORNIA
DEPARTMENT OF WATER RESOURCES
OROVILLE EMERGENCY RECOVERY – SPILLWAYS
TECHNICAL MEMORANDUM

Reviewer Initials: SV

Date: **November 2, 2017**

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SUBJECT: **Investigation and Initial Evaluation Cracking of Erosion Resistant Concrete Invert Panels in the FCO Spillway**

The first Erosion Resistant Concrete (ERC) panel was placed in the Flood Control Outlet (FCO) Spillway on August 4, 2017. During that panels' 14-day water cure, cracking on both the surface and on the sides of the panel were identified through onsite inspections (August 16th). As additional panels were placed, hairline cracks continued to be observed during the curing process despite adjustments to the concrete mix design and variation of the placement and finishing methods. This memorandum compiles the information available and identifies the planned steps to ensure the long-term durability and serviceability of the FCO Spillway chute invert.

Background

The design of the ERC invert panels in the FCO Spillway included the following proactive measures in the project drawings and specifications to minimize the risk of concrete cracking during construction:

- A maximum concrete placement temperature of 55 degrees F was instituted to minimize the heat of hydration.
- The top mat of reinforcement was interrupted with smooth bar dowels replacing the reinforcement at the adjacent panel joints, to allow relief of some top surface thermal expansion and overall shrinkage.
- Curing consisted of a fourteen-day (14d) water cure.
- Curing concluded with a four-day (4d) panel acclimation with the cure blankets following the specified water cure.
- A larger aggregate size was implemented, maximum of 2 inches (minimum 90% passing 1.5" sieve), to minimize the shrinkage potential per cubic yard.
- Silica fume was included in the mix for its early tensile strength.
- The mix utilized Type II cement and fly ash.

The initial ERC mix design was submitted by the contractor from their proportioning study. This initial mix, ERC_NOAE_HI, had a cementitious content of 800 pounds per cubic yard. The contractor placed panels 90E and 38E with the ERC_NOAE_HI mix design. DWR directed the use of a lower cementitious content concrete mix after collecting later compressive strength data from the initial proportioning study where passing break strengths were observed for the lower cement alternatives. The contractor then began using the approved ERC_NOAE_LO with a cementitious content of 660 lbs/cy. The ERC_NOAE_LO mix has a 28 day compressive strength exceeding the required design strength of 5,000 psi. Despite this change in mix design, a number of hairline cracks continued to be observed in subsequent panels following the removal of the cure blankets. DWR began to investigate, and extensively document, and monitor the cracking of the ERC panels within the FCO Spillway.

Evaluation of Observed Cracking

Documentation Efforts

The Oroville Emergency Recovery – Spillways (OER-S) team developed a system for the 2017 construction season's crack investigation, documentation, and monitoring that included:

- Mapping of cracks in at least one panel within every transverse row of panels placed.
- Installing temperature monitoring sensors in at least five placements.
- Evaluating the remaining invert panels according to the qualitative scale described below.

Table 1: Oroville Dam Flood Control Spillway ERC Panel Crack Rating System

Qualitative Scale	Random Crack Frequency [lft]*	Crack Width [mm]	Crazing Description**
1	<60	< 0.10	None to Minimal
2	60 – 150	<0.10	Minimal
3	60 – 150	>0.10 and < 0.20	Present but Confined
4	>150	>0.20 and < 0.35	Widespread
5	>150	>0.35	Widespread

* lft is measured as total linear feet of observable cracks.
** Crazing will be evaluated and reported but will not be part of the Crack Rating System.

The mapping efforts have occurred as soon as the panels became accessible following the curing requirements. Staff reevaluates the panels approximately 14 days and 30 days later; the exact interval varies depending on access and staff availability. Attachment 1 includes a summary of the present mapping and evaluation efforts.

Description of Cracking Observed and Possible Cause of Cracking

Cracking was anticipated due to the highly restrained nature of the FCO Spillway panels. The panels are designed to be restrained through numerous mechanisms: bonded with the leveling course concrete, anchored to the foundation, and interlocked by having continuous bottom mat reinforcement and keyways between adjoining panels. The features that produce the high level of restraint also produce a highly robust and durable spillway structure. By design, location, spacing and amount of reinforcement was intended to distribute cracking and keep it at a hairline level. American Concrete Institute (ACI) 224R provides general guidance on acceptable crack widths and describes in detail the cause and effects of both internal and external restraint in concrete structures.

Early Age Deformation and Cracking

The cracking observed with the ERC invert panels in the FCO Spillway chute to date appear to be the result of early age cracking, which is caused by thermal deformation (due to cement hydration) and/or shrinkage deformation (autogenous shrinkage and plastic shrinkage). Early age cracking is summarized within the following pages or can be found in detail within ACI 231R-10. Figures 1-4 consist of photos of the typical cracking observed on site.

Figure 1: Typical Cracking Observed

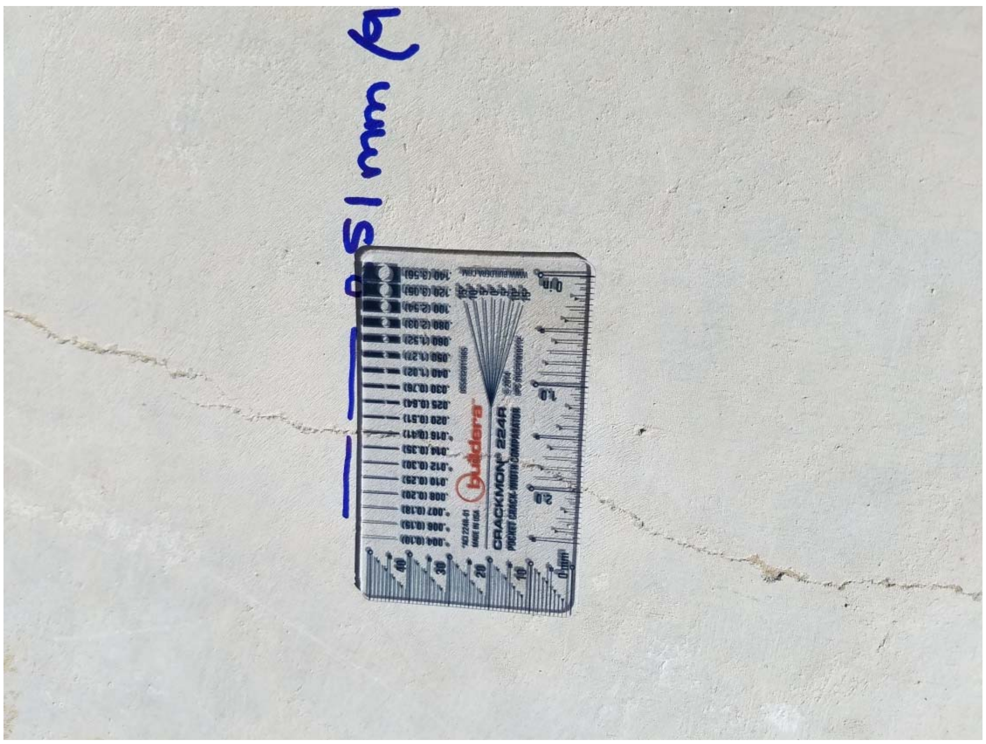


Figure 2: Typical Crack with Spalling and Raveling

Figure 3: Typical Through Cracking Observed

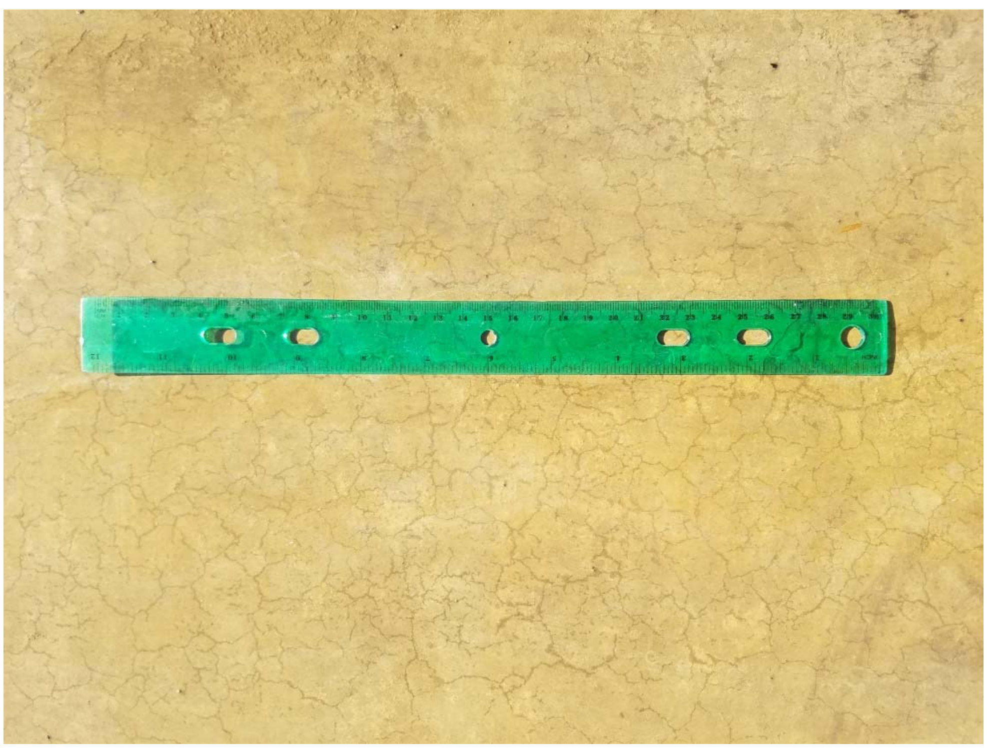


Figure 4: Typical Crazing Observed

Autogenous Shrinkage

Autogenous Shrinkage is a “change in volume due to the chemical process of hydration of cement, exclusive of effects of applied load and change in either thermal condition or moisture content” (ACI CT-13, pg 5). Sometimes referred to as fixed restraint cracking, autogenous shrinkage causes cracking when restraints are introduced within the concrete panel. In our case, the underlying leveling concrete was placed relatively thick (greater than concrete panels), allowed to cure (majority of shrinkage occurring prior to panel placement), and the surface was prepared to achieve a strong bond between the panels and leveling concrete. After placement of leveling concrete, anchors were drilled through the concrete into underlying rock and grouted with a high strength grout. The anchors extend into the concrete panel providing a fixed restraint while the underlying leveling concrete similarly restrains movement in the concrete panels.

It appears the majority of cracking visible is autogenous cracking, due primarily to the concrete being restrained by both underlying leveling concrete and anchors extending into the panel. After reviewing the mapping of cracks overlaid on the anchors, it is apparent that cracking is primarily between anchors supporting this theory.

Autogenous shrinkage cracking “is a special case of drying shrinkage that results from self-desiccation (internal drying) in concretes with water-cementitious material ratios (w/cm) below 0.42, but most often w/cm below 0.3” (ACI 224R-01). The ERC_NOAE_LO design w/cm ratio is 0.38 and typically arrives at the placement between 0.30 and 0.38. According to ACI 224R01, autogenous shrinkage has been reported to have occurred mainly with high cementitious material concretes and occurs without a loss of moisture from the bulk concrete. Autogenous shrinkage typically increases with increasing temperature, cement content, and cement fineness.

Thermal Shrinkage

Temperature gradients in a concrete structure can result in differential volumetric changes, resulting from heat of hydration and/or by the weather conditions. Currently, DWR has installed and monitored panels 31B, 44B, and 99B for temperature differentials. Panels 35D and 100D were recently installed and monitoring is underway. Attachment 2 shows both the heat of hydration change with time and the temperature increase (center of the panel) from the max placement temperature of the completed temperature monitored panels. Additionally, the instrumentation has reported the maximum thermal differential between near panel surface and internal reading of each panel as 16.4 degrees F, 18.7 degrees F, and 19 degrees F, respectively. DWR suspects that the lower temperature differential observed in panel 31B occurred because the location remained shaded for most of the day and the ambient temperatures were typically 4 and 7 degrees lower than the middle and lower chute locations, respectively. The thermal gradients never measured any greater than 35 degrees F, which suggests thermal shrinkage is not a primary cause of the observed cracking. However, the temperature differential measured suggests that it is likely a contributor of the internal stresses, which caused cracking to occur.

Plastic Shrinkage

According to ACI 224R01, plastic shrinkage cracks occur "when moisture evaporates from the surface of freshly placed concrete faster than is replaced by bleed water… and is usually associated with the rapid loss of moisture caused by a combination of factors that include high air and concrete temperatures, low relative humidity, and high wind velocity at the surface of the concrete."

Windy placement conditions and delayed application of cure blankets may result in an increased evaporation on the finish surface, see Figure 5. In addition, poor water cure management for the duration of the required 14 days subjects the panels to potential drying and wetting cycles. Several instances occurred where the contractor did not immediately install water cure on the panel following the finishing efforts, as well as instances where the water cure was terminated or disrupted by other onsite operations introducing the variability in moisture cure. ACI 224.1R notes that "plastic shrinkage cracks begin as shallow cracks, but can become full-depth cracks later in the life of the concrete." The contractor has attempted to mitigate the above mentioned moisture loss issues during placement and finishing efforts by using wind barriers and fogging, as well as securing the wet cure blankets to the surrounding formwork/panels as a post placement water cure management effort.

Figure 5: Cracking observed in 30C four hours after finishing

Crack Mapping Results

As can be seen in Attachment 1, cracking observed in the spillway was random with average panel ERC crack widths ranging from less than 0.01 to 0.3 mm and an average width of 0.18 mm. The average crack frequency on the panel surface was found to be 80 lft. Most of the edge cracking appears to arrest at the top mat of reinforcement with some progressing through the entire panel. Table 2 shows a breakdown of the ratings of the thirty-four panels mapped to date.

Table 2: Breakdown of Scale Values for Mapped Panels

Qualitative Scale	Number of Panels rated in each Scale	Percent of Total Mapped Panels
0	1	1.75%
1	9	16%
2	21	37.5%
3	20	35.75%
4	5	9%
5	0	0%
TOTAL	**56**	**100%**

It was also observed that the cracking found on panels A and F were less with an average scale value of 2 and average frequency of 35 lft. The average scale value found for B through E panels was 3 and the average frequency was 125lft. The A and F panel geometry has a larger concrete cross section, with a depth of 4.5ft, than panels B through C, with a depth of 2.5ft.

Findings and Recommendations

ACI 224R01 section 2.1 states: "Cracks need to be repaired if they reduce the strength, stiffness, or durability of the structure to an unacceptable level, or if the function of the structure is seriously impaired." DWR along with its consultants have evaluated the current ERC invert panel crack conditions and determined that at this time, the cracking does not impair the structure and therefore, at this time does not warrant repair. DWR is committed to continue to monitor and evaluate the cracks regularly throughout 2017 flood season and again throughout the 2018 construction season. This will allow the panels to reach a state of volumetric equilibrium to allow for a determination if conditions continue to change prompting the need for remedial measures.

DWR's OER-S team plans to expand the ERC crack investigation efforts to determine and test additional construction measures and concrete design mix changes that could minimize cracking in the concrete used during the 2018 construction season. The construction measure changes that will be evaluated in the off-season include:

- Modifying the cure type and duration.
- Researching the use of products to aid in protecting the concrete during finishing and inclement weather.
- Evaluating mix design changes which may include:
    - Lowering the cement content.
    - Increasing the coarse aggregate volume.
    - Using shrinkage reducing admixtures, and/or expansive cements.

References

ACI CT-13
ACI 224R01
ACI 224.1R07
ACI 231R-10

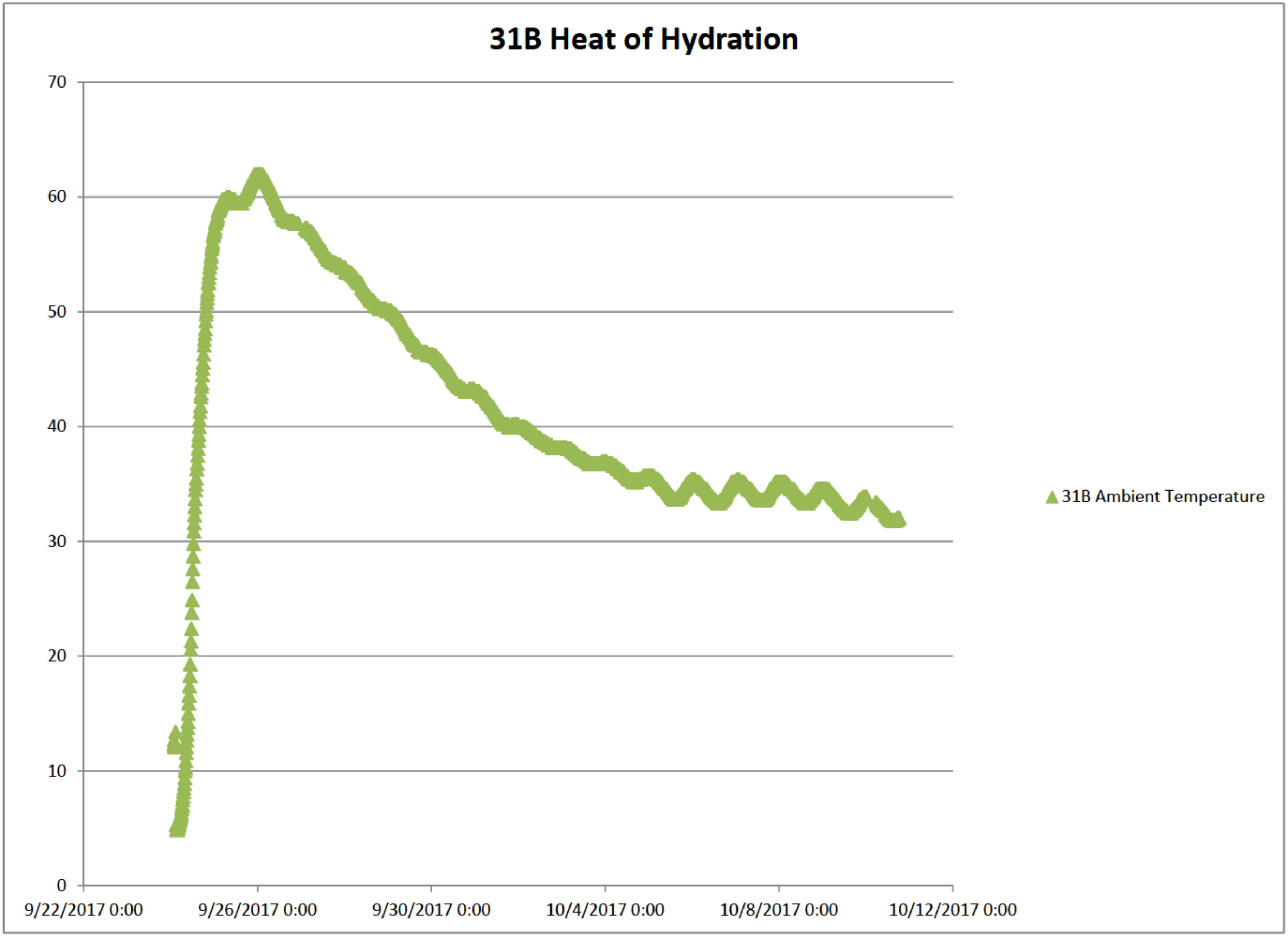
Attachments

- Attachment 1: Spillway Plan View, Summary Table of Crack Monitoring, and Crack Maps of Current Monitored Panels
- Attachment 2: Heat of Hydration Plots for Three Temperature Sensor Monitored Panels

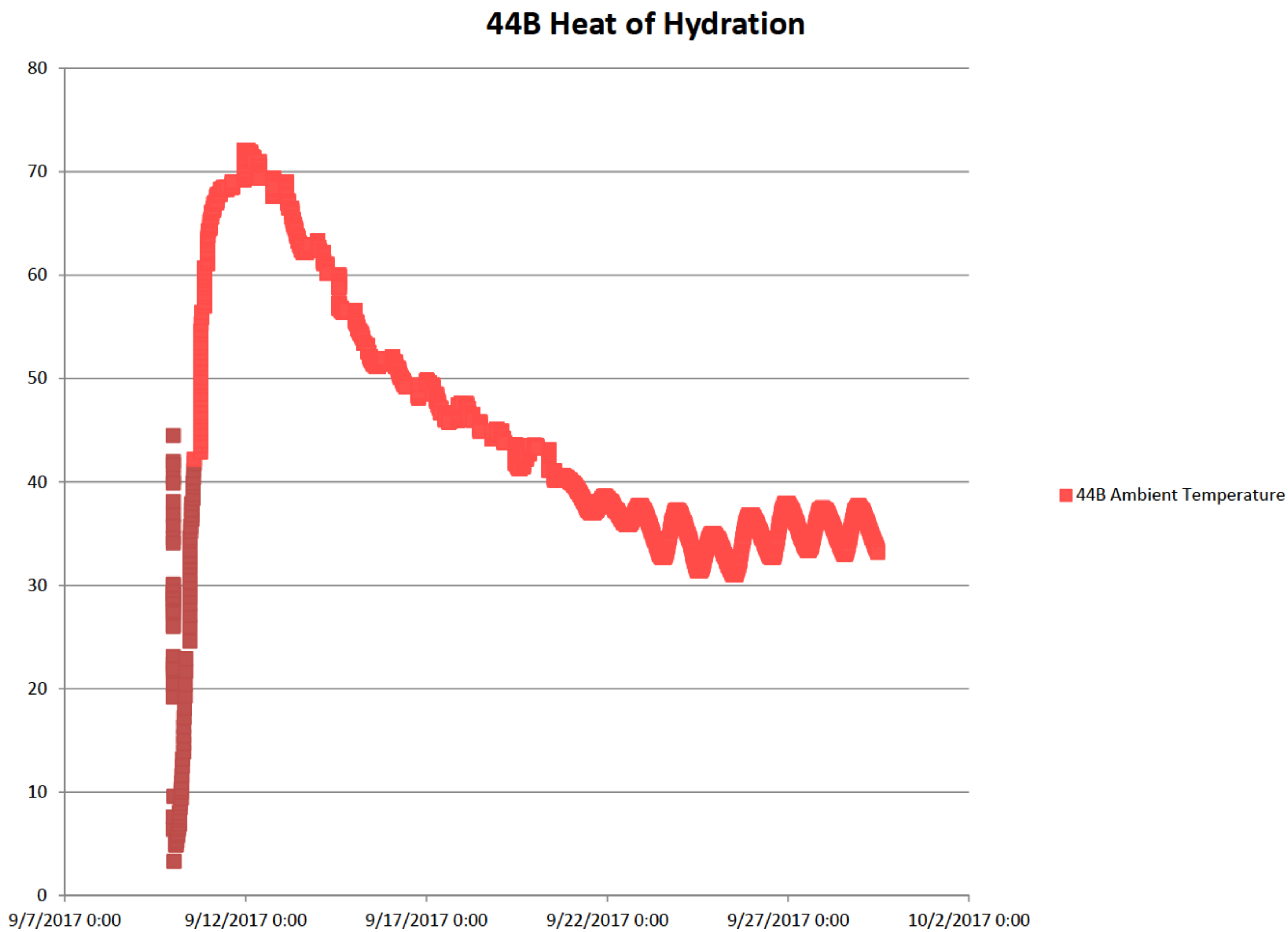
Attachment 1 has been redacted for CEII

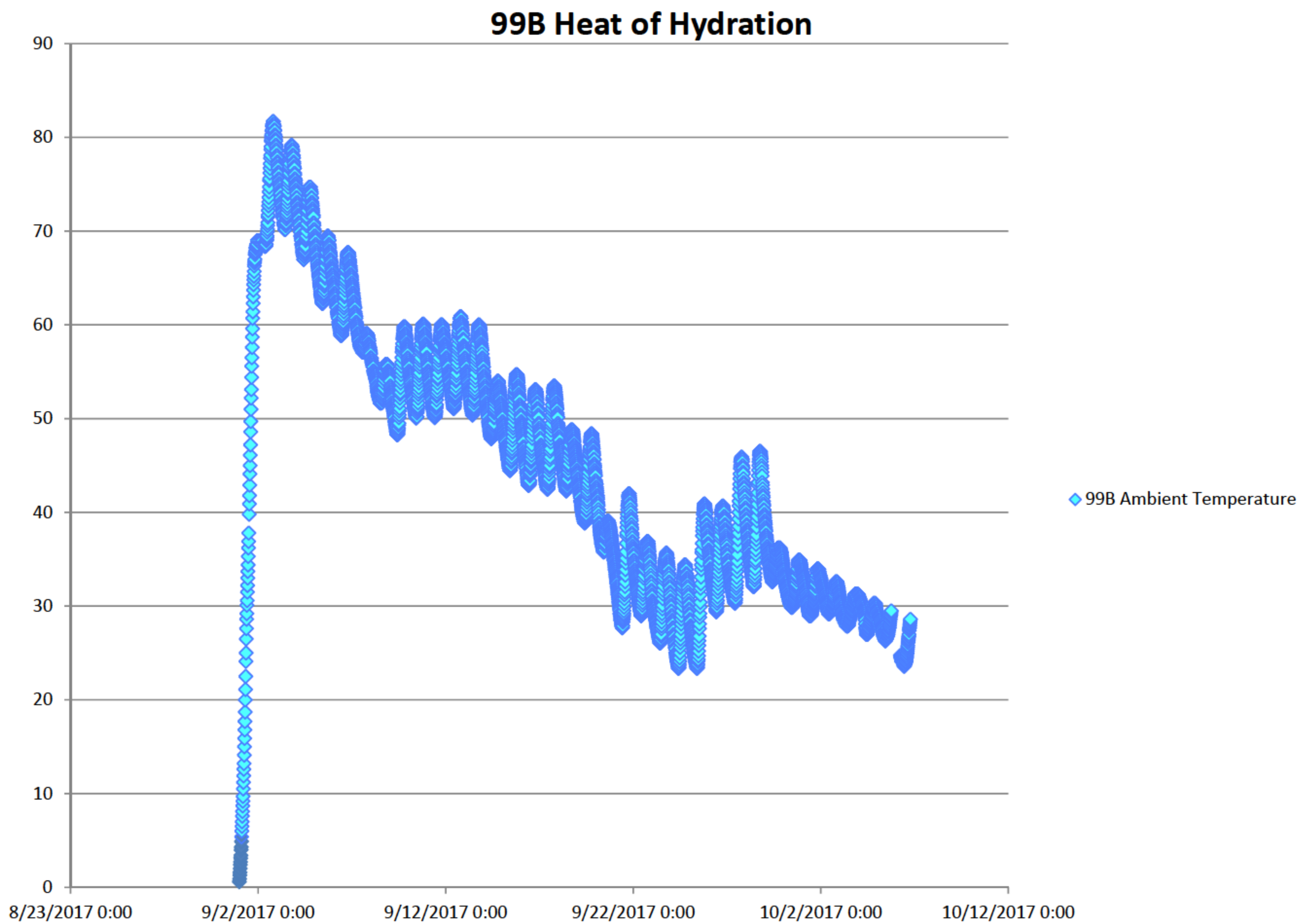
Attachment 2

Heat Hydration Plots for Three Temperature Sensor Monitored Panels



31B Heat of Hydration
70
60
50
40
30
20
10
0
9/22/2017 0:00
9/26/2017 0:00
9/30/2017 0:00
10/4/2017 0:00
10/8/2017 0:00
10/12/2017 0:00
31B Ambient Temperature


44B Heat of Hydration
80
70
60
50
40
30
20
10
0
9/7/2017 0:00
9/12/2017 0:00
9/17/2017 0:00
9/22/2017 0:00
9/27/2017 0:00
10/2/2017 0:00
44B Ambient Temperature



99B Heat of Hydration
90
80
70
60
50
40
30
20
10
0
8/23/2017 0:00
9/2/2017 0:00
9/12/2017 0:00
9/22/2017 0:00
10/2/2017 0:00
10/12/2017 0:00
99B Ambient Temperature